ENERGETIC PROTONS FROM THE SOLAR FLARE OF MARCH 24, 1966

S. W. KAHLER, J. H. PRIMBSCH, and K. A. ANDERSON

Physics Dept. and Space Science Labo.,
University of California, Berkeley, Calif.

(Received 18 March, 1967)

Abstract. Ten to 100 meV protons from the solar flare of March 24, 1966 were observed on the University of California scintillation counter on OGO-I. The short rise and decay times observed in the count rates of the 32 channels of pulse-height analysis show that scattering of the protons by the interplanetary field was much less important in this event than in previously observed proton flares. A diffusion theory in which $D = Mr^{\beta}$ is found to be inadequate to account for the time behavior of the count rates of this event. Small fluctuations of the otherwise smooth decay phase may be due to flare protons reflected from the back of a shock front, which passed the earth on March 23.

1. Introduction

The first Orbiting Geophysical Observatory (OGO-I) was launched into orbit on September 5, 1964. The orbit is very eccentric, with an initial period of about 64 hours and an apogee of about 24 earth radii. It carries 20 different experiments designed to gather information of geophysical, solar, and astronomical interest

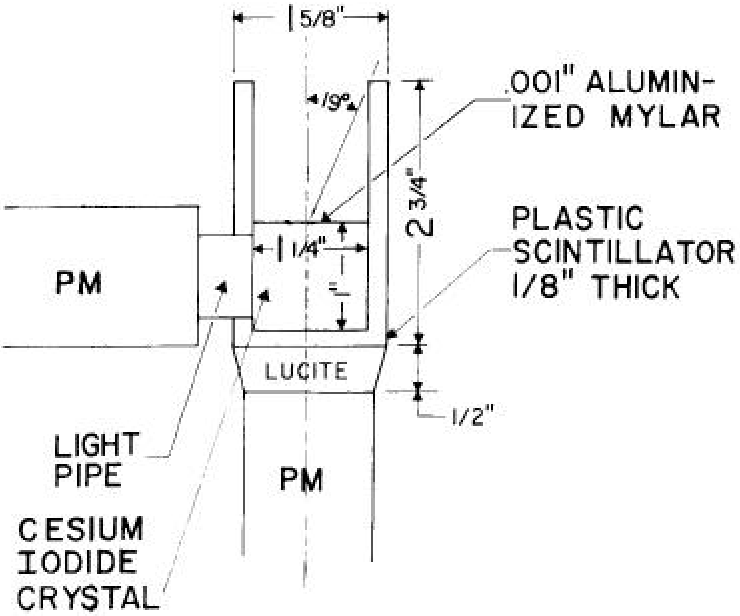

Fig. 1. The University of California CsI scintillation counter.

Solar Physics 2 (1967) 179–191; © *D. Reidel Publishing Company, Dordrecht-Holland*

(LUDWIG, 1963). One of these experiments was designed to measure solar cosmic ray fluxes from 3 to 90 MeV. The detector is shown in Figure 1. It consists of a cesium-iodide crystal 1 inch thick and $1\frac{1}{4}$ inch in diameter viewed from the side by a RCA-7119 photomultiplier. A plastic scintillator surrounds the crystal on the bottom and side and is viewed from below by a second photomultiplier. The entrance aperture to the cesium iodide scintillator is covered with 7-milligrams cm^{-2} aluminized mylar to exclude light. Pulses from the crystal are amplified and fed into a 32-channel analyzer. Pulses from the plastic scintillator gate out these from the cesium-iodide crystal to insure that only particles coming through the detector opening and stopping in the crystal are analyzed. The detector is calibrated in-flight in two ways: from an Americium-241 source with an effective energy loss of 4.4 meV and from the energy of the protons which just escape from the cesium-iodide crystal. For the 1-inch thick crystal this energy is 90 meV. Alpha particles may deposit greater energy but the flux will be much lower. No direct means is provided for discrimination of electrons, protons,

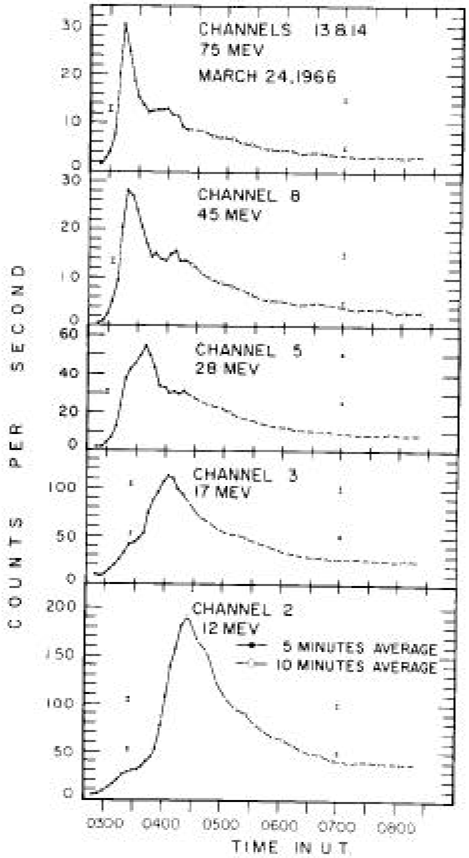

Fig. 2. Uncorrected count rates of selected channels during the March 24, 1966 solar proton event. Data before 0430 was averaged over 5-minute intervals and afterwards over 10-minute intervals. The dispersion in the peak fluxes can clearly be seen.

and alpha particles. No electrons in this energy range have been identified in association with solar flares except for the July 7, 1966 event (McDONALD, 1966) and the fluxes of the 3 to 12 meV electrons detected in the interplanetary medium by CLINE *et al.* (1964) are below the detector background flux.

The detector is mounted in the Solar Oriented Experimental Package 1 (Soep-1). The configuration of this spacecraft has been described by LUDWIG (1963). It was intended that the spacecraft be space stabilized in such a way that the detector axis would always point to the sun. However, a malfunction prevented this orientation. The experiment has also been somewhat limited by a failure in the anti-coincidence system. This has resulted in high background rates due to the galactic cosmic rays. A discussion of these problems and their effects on the data is presented in the Appendix to this paper. Although we have been unable to obtain reliable absolute flux measurements, the experiment has provided good time histories of protons in the 10–90 MeV range from the solar flare of March 24, 1966.

2. The Flare of March 24, 1966

On March 24, 1966 a flare occurred in McMath plage region 8207, which was observed in Hα light by four observatories. It began about 0225 UT, reaching a maximum phase at $\approx$ 0238 UT. A SCNA was observed with a maximum at 0229, indicating the production of x-rays. Other ionospheric disturbances were observed which had maxima within several minutes of the optical maximum. In addition, strong type-IV continuous radiation in the 5–250 Mc/sec range was seen from 0030 to 0523 at the Culogora Solar Observatory of the C.S.I.R.O. The importance of the flare was 2, and it was located at a longitude of W 42 and a latitude of N 22. The plage region was very active and had produced a large number of flares and subflares prior to the March 24 event.

3. Data Analysis

At the onset of the event the satellite was on an inbound sector of its orbit. From the flare onset until the end of the data coverage the sun-earth-satellite angle was between 32° and 36° and on the dawn side of the earth. The data presented here were recorded when the satellite was well outside the earth's radiation belts.

Continuous tape recorded data are available from 2202 UT on March 23 to 0826 UT on March 24. The count rates of each of the channels averaged over the time interval from 2202 UT on March 23 to 0242 on March 24 were used as the background flux during this event. Another interval of usable data was received from 2004 UT to 2154 UT on March 24.

The first protons were seen at 0250 UT, hence the travel time was only about 20 minutes if the injection time is assumed to coincide with the optical maximum. Figure 2 shows the total count rates in several selected channels. It can be seen that the highest channels which count the highest-energy protons peak earliest and then the lower-channels peak successively later. Figure 3 shows the times during which each

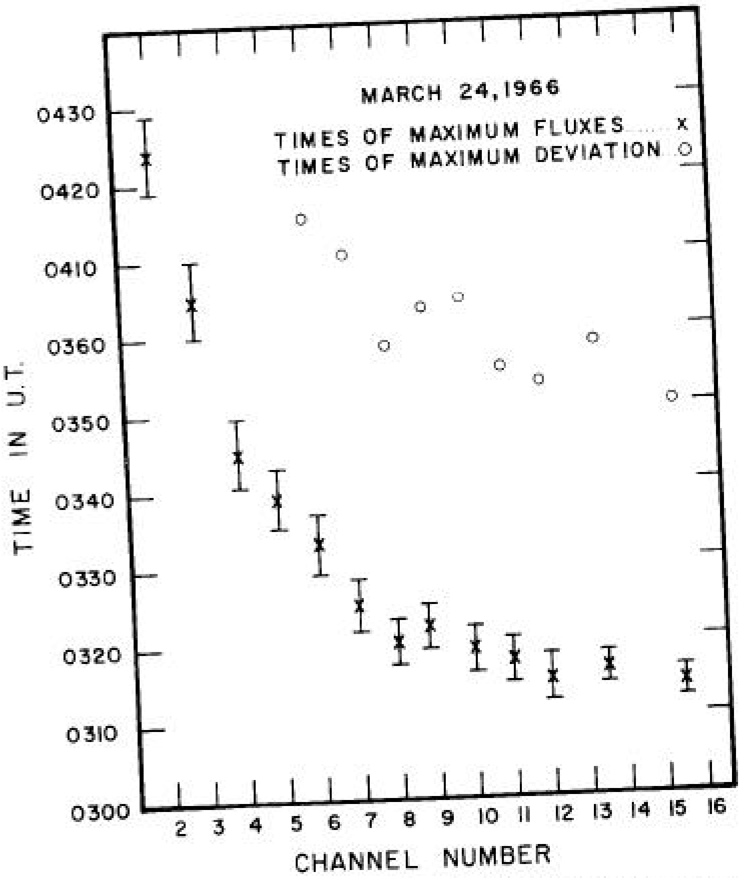

Fig. 3. Times of maximum fluxes in each of the channels. The error bars represent the estimated uncertainties in choosing the times. Channels 13 and 14 and channels 15 and 16 were combined for this analysis. The times of maximum deviation are the times at which the count rates of the channels show the greatest deviation from smooth decay.

of the channels reached its peak count rate. If one assumes that the distances traveled by the protons seen in the peaks of the different channels are equal, that is, that the points of Figure 3 can be fit by a curve of the form $t \sim E^{-1/2}$, then the travel distance is about 2.05 AU for the peak fluxes of each channel. Bryant *et al.* (1964) did a similar analysis for the September 28, 1961 event and found a mean travel distance of ≈ 10 AU for the peak flux of each energy region. Qualitatively, one might expect a difference since the September 28 flare occurred at E 30 and the March 24 flare at W 42. Thus, the protons from the former evidently diffused across interplanetary field lines while the protons from the latter could travel predominantly along the field lines to reach the earth.

Good fits to the diffusion model worked out by Parker (1963) have been obtained for three solar proton events by Krimigis (1965).

In this theory he assumes that the diffusion coefficient takes the form

$$D = Mr^{\beta}$$

where r is the heliocentric radial distance, and M and β are parameters dependent on the particle energy E. Log. $It^{3/(2-\beta)}$ is plotted against $1/t$ for different values of β. The proper value for β is taken to be that which gives the closest fit to a straight line. Krimigis got reasonably good fits using data from three solar proton events. The event of 24 March 1966 has also been plotted according to Krimigis' method, as shown in Figure 4. In both plots it is obvious that no value of β will yield a straight line. The strong peak fluxes are responsible for a definite curve in all the plots regardless of the value of β. The application of a correction factor to the diffusion equation to account for the finite travel times at the onset of the events (WEBBER, 1964) has the effect of increasing the curvatures of the plots. It also appears that the fluxes corresponding to large t are smaller than predicted, since the points on the right-hand sides of the graphs in Figure 4 turn down except for $\beta = 1$, in which case the curve bends upward. This behavior for large t has also been seen in solar electron events on IMP-III (LIN and ANDERSON, 1966b). The proton event reported here is very similar to the electron events in that in both cases injection occurred near the base of the interplanetary field lines passing by the earth, and the rise times and delay times of the fluxes were very short. It appears in these cases that the particles are traveling along the field lines with very little scattering. Hence, it is not surprising that a diffusion model gives such a poor fit to these events. Another reason to expect little scattering for this particular event is that Kp was very low on March 24. The field was undoubtedly very well ordered at this time since a plasma cloud which caused an SC on March 23 had stretched the field lines behind it. Further evidence for the well-ordered nature of the field lines can be deduced from the fact that an electron event associated with this flare was also observed on IMP-III by LIN and ANDERSON (1966a) and was found to have an unusually short delay time. The short travel times of both electrons and protons and the location of the flare at W 42° suggest that the earth was in the cone of propagation for this event. In this cone, particles travel along the field lines with very little scattering. LIN and ANDERSON (1966b) found that this cone of propagation has an opening angle of ≈ 30° for simple electron events. Figure 5 shows the geometry of the situation.

Further evidence for the cone of propagation can be seen from a class-2 flare on March 23. This flare occurred at W 32 and reached Hα maximum at ≈ 2300 UT. It occurred in the same plage region as the March 24 flare and was separated from the latter flare by less than four hours in time and by approximately 10° of solar longitude. The time behavior of the two events is considerably different, however. No increase in counting rates was seen until after 0000 UT on March 24. Ion chamber data from OGO-III (WINCKLER, 1967) and IMP-III also show no increase until after 0000 UT on March 24. Thus, a full hour elapsed before any protons were observed from the March 23 event, but counting rates were seen to be rapidly increasing within a half hour of the March 24 event. Evidently, protons from the earlier event had to diffuse across field lines either at the sun or in interplanetary space to get to the earth. These

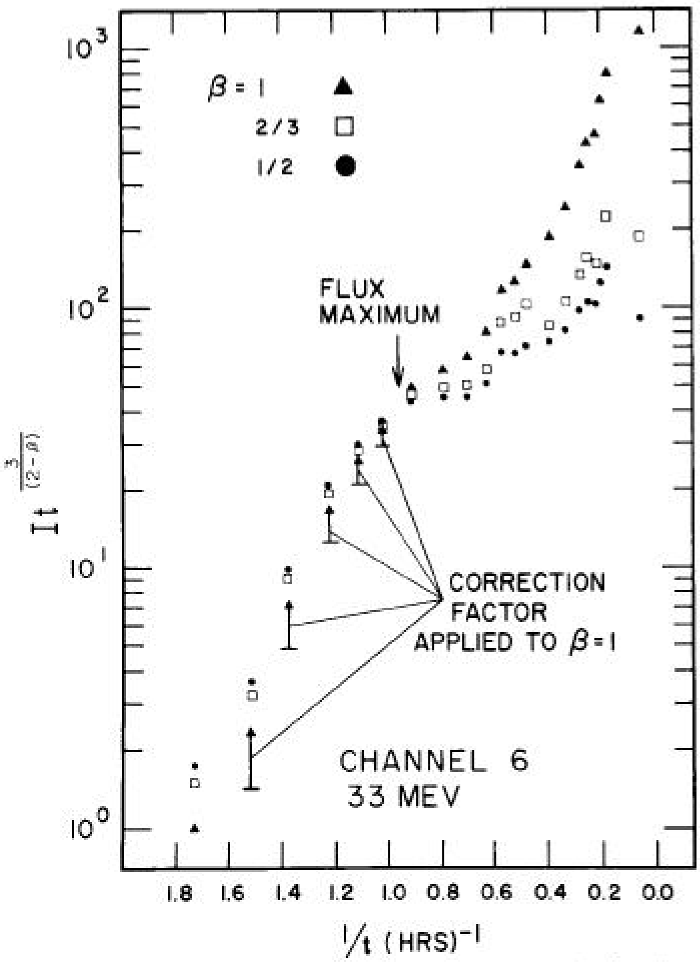

Fig. 4a. Krimigis' theory applied to the corrected count rates of channel 6 for $\beta = 1$, $\frac{2}{3}$ and $\frac{1}{2}$. The correction factor has been applied to the plot of $\beta = 1$.

two events illustrate the different kinds of behavior of solar proton events depending on whether the earth is in the cone of propagation for the flare. When the earth is in the cone of propagation, we see events like the March 24 event and the 40 keV electron events. When the earth is outside the cone, the protons must diffuse across field lines giving rise to a diffusion type event such as the March 23 event. Because the flares were separated by less than four hours in time, it is assumed that the interplanetary field configuration did not change significantly between events. The March 23 event was several orders of magnitude lower in flux than the March 24 event so that the counting rates of the latter were not significantly affected by the former.

One of the events for which Krimigis obtained a good fit to the diffusion model was the proton event of July 18, 1961. This event had a history very similar to the March 24, 1966 event. An earlier flare on July 15, 1961 was presumably the source of a

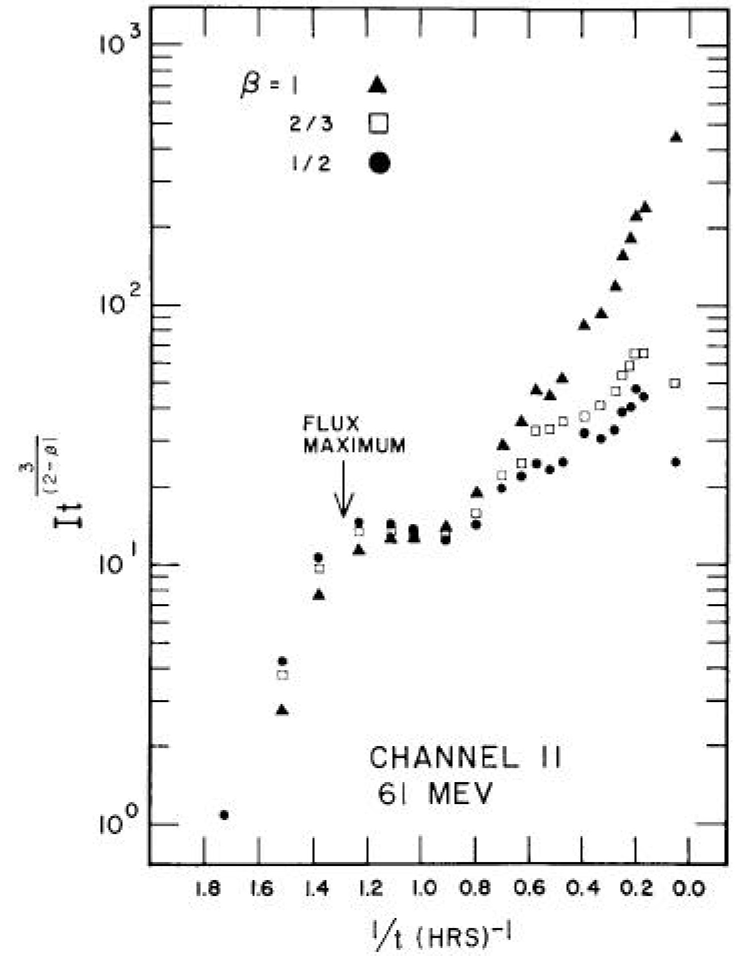

Fig. 4b. Krimigis' theory applied to the corrected count rates of channel 11.

geomagnetic storm, which began on July 17 at 1827 UT. The July 18 flare occurred at W 58, in the same plage region as the earlier July 15 flare. It might seem that interplanetary conditions were favorable for the occurrence of a fast rise and fast decay event similar to the March 24, 1966 event. Although a rapid rise was seen in the neutron monitor data for the July 18 event (McDonald, 1963), Krimigis found a diffusion constant for the $E > 40$ meV protons, which was smaller than the diffusion constants for similar energies of both the September 28, 1961 and the April 15, 1963 events. However, these latter two events occurred at E 30 and W 03, respectively. The *Kp* indices for July 18 may offer a clue to the behavior of this event. The geomagnetic storm began at 1827 UT on July 17. *Kp* was very high from the onset until after July 18. If we take the high *Kp* to be an indication of considerable interplanetary disturbances, it can be seen that the 40 meV protons had to diffuse through the

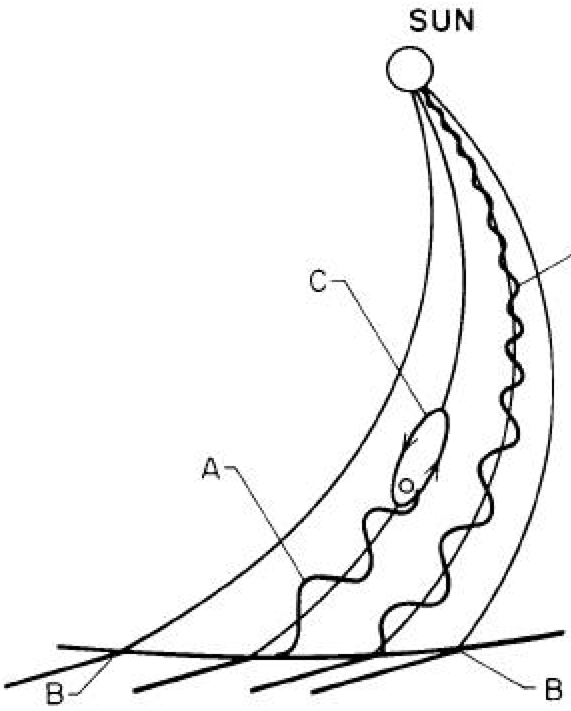

Fig. 5. The idealized interplanetary magnetic field at the time of the March 24 flare. Protons reflected from the shock at *B* may have traveled back to the earth along path *A* and been seen by the OGO-I detector at *C*. *D* is the idealized path of a first 'wave' proton.

turbulent region to reach the earth. If the July 18 event had occurred about 24 hours later when *Kp* was low, the event may have resembled the March 24, 1966 event. The history of events preceding the March 24 flare is discussed below.

It can be seen in Figure 2 that the typical behavior of the count rate in a given channel is a very smooth and rapid onset followed by a smooth decay, until at some time near 0400 UT there is either an anomalous increase or a lack of decrease in the counting rate. After approximately half an hour of the anomalous behavior the decay proceeds smoothly. This behavior is clearly seen in channel 5 and higher channels. It is not so obvious in channels 2, 3, and 4. In view of the well-behaved nature of the rest of the event, it is worth trying to explain this anomalous behavior at $\approx$ 0400 UT. It is not likely due to injection of more solar protons from another flare since no other flares were reported until 0719 UT.

It can be seen in Figure 3 that there is a dispersion in the times of maximum deviation from a smooth decay for the channels plotted. For several of the channels it is not at all obvious exactly what these times are since the count rates fluctuate too much to enable one clearly to pick a single maximum, but the general trend is clearly that the deviation maxima occur at later times in the lower-energy channels. This dispersion can be used to rule out another obvious possibility, namely that the 0400

UT decay anomaly is due to the filamentary nature of the interplanetary field as described by BARTLEY *et al.* (1966) from measurements on Pioneer 6. One would expect all the fluxes to peak simultaneously as the earth passed through the middle of the filament. Since this is not the case, let us consider the possibility that the particles in the decay anomaly left the sun at the same time that the main group did but traveled a greater distance before they were observed at the earth. Two cases can then be considered. The first is that they traveled along a much longer field line to reach the earth. The second case is that they went past the earth and were reflected back. In considering the first case, it can be seen from Figure 3 that the anomalous particles took an extra $\approx$ 40 minutes to reach the earth. Since particles seen in the main counting rate peaks traveled for $\approx$ 50 minutes, an extra 40 minutes of travel time implies that the associated filament should be a very extended one, a difficult idea to accept in view of the well-ordered and quiet conditions present in the field, as seen in the discussion above. A final objection is that the count rates of channels 2 and 3 with the lowest-energy protons show the least deviations from smooth decay. Since the lower-energy protons have the smaller gyroradii, one would expect that they would be the most sensitive to changes of filaments.

The hypothesis advanced here to account for the deviations from smooth decay is that these anomalous fluxes are protons which have been reflected from a shock wave associated with a sudden commencement which occurred at 1133 UT on March 23. In order to understand the phenomenon clearly, it is necessary to consider the events which preceded the March 24 flare. As it crossed the solar disk, plage region 8207 was extremely active. A class-2 flare was observed at 1000 UT on March 20. This flare was probably responsible for the sudden commencement at 1133 UT on March 23. The Deep River Neutron monitor showed a Forbush decrease at this time, which did not begin to recover until the end of March 24. Assuming a constant velocity for the shock wave and a travel time of 73.5 hours, the velocity was 566 km/sec. Then at 0300 UT on March 24 it was 0.21 AU past the earth. If it took 20 minutes to travel each way to account for the $\approx$ 40-minute delay in the anomalous flux, a proton traveling in a straight line from the earth to the shock and back again would require a velocity of 2.6×10^9 cm/sec. This is obviously a minimum velocity since the protons can be expected to expend part of their motion in spiraling and being scattered by the interplanetary field in addition to undergoing some kind of complicated motion at the shock front itself. The travel distances for the reflected protons will also be greater because the protons will not follow the sun-earth line back to the shock front, but must follow the general spiral field behind the shock. The velocities of the protons observed in channels 6 to 16 are 7.5 to 12×10^9 cm/sec, so that the protons could travel a distance of 3 to 5 times the rectilinear distance. It has been assumed here that the initial 'wave' of particles as seen in the very sharp maxima is what is being reflected to produce the deviation maxima. Since the lower channels, especially 2 and 3, have such broad maxima, it is not surprising that no easily discernible flux due to reflection can be seen.

By knowing the fluxes in the initial 'wave' of protons and by estimating the fluxes in the reflected component, a crude kind of reflection coefficient can be estimated. This coefficient has the value ≈0.12. It must be pointed out that the detector has directional response characteristics, which make the interpretation of this coefficient somewhat difficult. The earth's magnetosphere also must play a role, probably in blocking some of the reflected protons.

Pursuing this hypothesis further, one would expect the dispersion in the times of maximum deviations to increase to the times of maximum flux in Figure 3. This is not clearly the case, although the velocities of the protons observed in channels 6 to 16 vary by a factor of nearly 2. However, as pointed out before, the times of maximum deviations are only a best guess for each channel. The low fluxes of anomalous particles make the times difficult to estimate. It is also possible that the low-energy protons are reflected first, perhaps in the turbulent region behind the shock, while the protons of higher energies penetrate farther before reflection. Such an effect would tend to reduce the expected dispersion of reflected protons.

One general kind of theory which cannot be ruled out is particle storage at the sun. It can be conjectured that a cloud of trapped particles was released 40 minutes after the flare maximum. While this theory cannot be directly ruled out by observation, it implies storage of protons of energies of the order of tens of meV. In events where protons have been seen long enough after the original flare to consider them as having been trapped, as for example in the September 28, 1961 event (BRYANT *et al.*, 1962), the protons were in the few-meV range with a steeply decreasing energy spectrum.

A final value derived from the data of this event was the ratio of the proton to alpha flux at ≈38 meV/nucleon. The count rates of all the channels were integrated from the start of the event to 0826 UT on March 24. The calculated ratio is 174 ± 50 where the error is due mainly to uncertainties in the interpretation of the energy levels of the channels. This value is fairly large compared to flares previously studied by FICHTEL (1964).

Appendix

1. *Anti-coincidence failure.* – As a result of the failure of the anti-coincidence system a large background was introduced since the effective geometry factor is 130 cm^2 sr for the galactic cosmic rays. The total count rate of all channels agrees well with an assumed cosmic ray flux of $0.2/\text{cm}^2$ sec sr above 100 MeV. A typical spectrum due to primary cosmic ray effects is shown in Figure 6. The peak in channel 3 is due to minimum-ionizing protons, which leave 18 MeV in the crystal if they traverse the 1-inch thickness. The path lengths of the particles in the crystal can vary from 0 to 1.6 inch, and one gets the counts distributed over several channels. This peak provides a rough calibration of the detector. The second peak in channel 15 is harder to explain. A small peak is expected at about 72 meV due to minimum ionizing alpha particles. The count rate expected in the peak agrees fairly well with the observed count rate, but the sharpness of the peak is rather strange in view of the wide range of path lengths possible. The time behavior of the counts in this peak indicate that it is

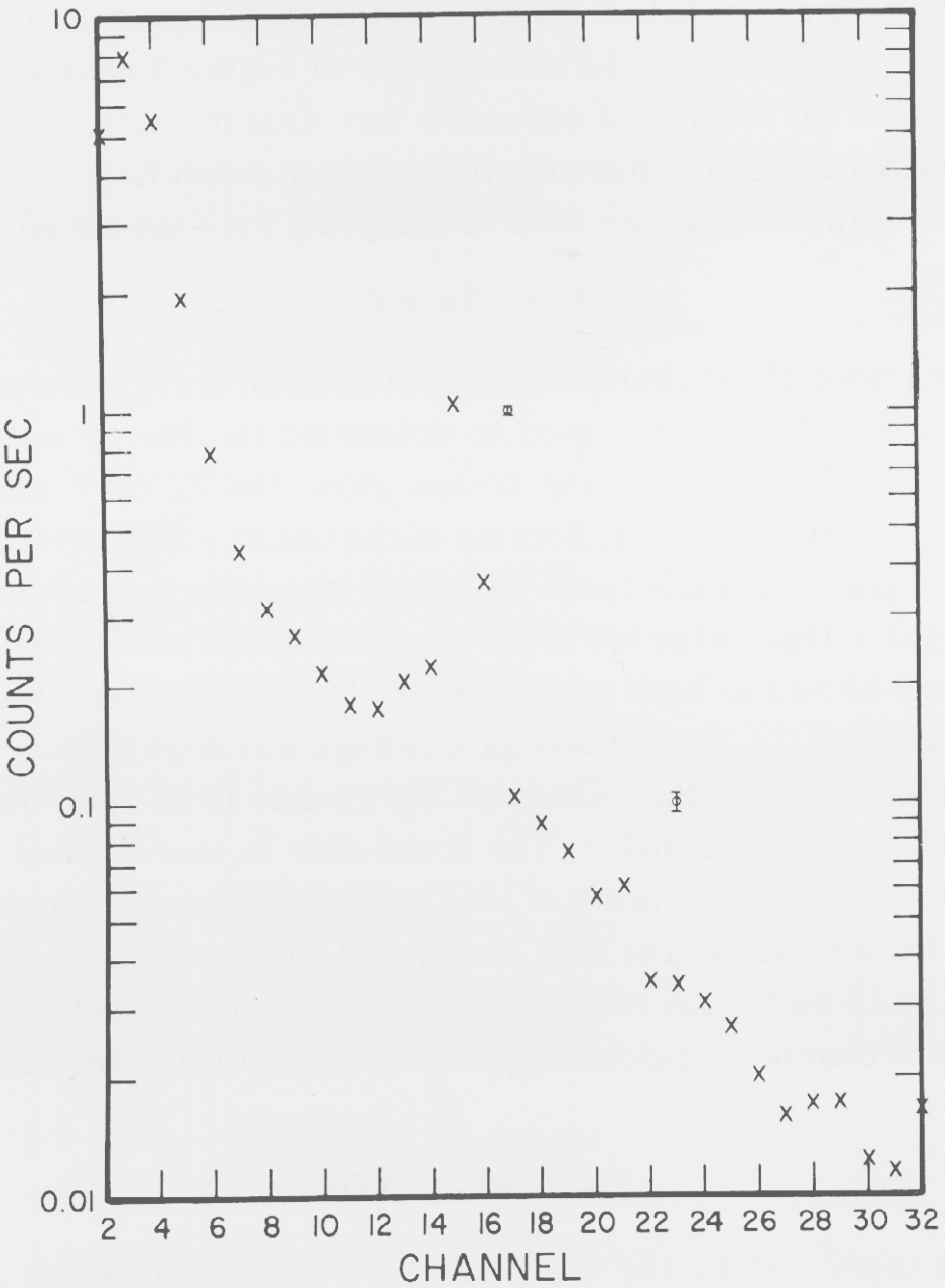

Fig. 6. A typical background of the University of California OGO-I CsI scintillation counter.

associated with the spacecraft operation and may be partly due to electrical interference. The count rate in the peak varies slowly in time, with noticeable changes taking place only after weeks of observing time.

The malfunction of the anti-coincidence makes it difficult to obtain reliable absolute proton and alpha fluxes. A comparison of the data from this event with riometer data (MASLEY, 1966) has shown that the total counting rate of the OGO detector is 6 to 8 times higher than if the anti-coincidence were working. Since protons of less than 16 MeV are constrained to enter the crystal through the detector opening, it is only the protons of greater energy that will cause the main difficulties. Because of the nature of the geometry of the crystal most higher-energy protons can be expected to lose a substantial amount of their total energy in the crystal. Early in the event the low energy channels are affected by the high-energy particles as can be seen from the shoulders preceding the counting rate maxima in channels 2, 3 and 5 in Figure 2. As the event proceeds, the energy spectrum becomes steeper, and a counting rate of a given channel is less affected by protons of higher energies. So the greatest errors are early in the event, before the peak in the counting rate of the given channel. The effect on the validity of the diffusion curves of Figure 4 is to increase the values of the points plotted for the time of maximum flux. Qualitatively, a correction to these curves would increase the curvature for the points at small t.

The energies of the 31 channels used in analyzing the data are given by

$$E = 5.5n + 0.5$$

where n is the number of the channel and E is the mean energy of a particle recorded in that channel. The three points used to determine the energy setting were the 18 meV peak due to minimum-ionizing cosmic rays, the 72 meV minimum-ionizing alpha peak, and the 90 meV cutoff. Because of the uncertainties involved, the nominal energies of the highest channels could be wrong by as much as 10–15 meV.

2. *Gain changes.* – During the life of the experiment, the peak at ≈ 72 meV has been as low as channel 13 and as high as channel 16. During the event discussed here this peak stayed in channel 13, so that any gain change was negligible.

During the early life of the spacecraft the counts from the Am^{241} calibration source were recorded in channel 2. The count rate in this channel decreased with subsequent orbits, until in the Spring of 1965 no counts from the source were recorded in channel 2. This was due to the slow increase of the lower edge (minimum energy) of channel 2. The 18 meV peak moved from channel 4 to channel 3 during this time. The lower edge of channel 2 did not appear to change during the flare observations.

Acknowledgments

This work was supported by the National Aeronautics and Space Administration under contract NAS 5-2222.

References

Bartley, W. C., Bukata, R. B., McCracken, K. G., and Rao, U. R.: 1966, 'Anisotropic Cosmic Radiation Fluxes of Solar Origin', *J. Geophys. Res.* **71**, 3297–3304.

Bryant, D. A., Cline, T. L., Desai, U. D., and McDonald, F. B.: 1962, 'Explorer 12 Observations of Solar Cosmic Rays and Energetic Storm Particles after the Solar Flare of September 28, 1961', *J. Geophys. Res.* **67**, 4983–5000.

Bryant, D. A., Cline, T. L., Desai, U. D., and McDonald, F. B.: 1964, 'Velocity Dependence and Source Spectra of Solar Proton Events', in *AAS-NASA Symposium on the Physics of Solar Flares* (edited by W. N. Hess), NASA SP-50, Washington, pp. 289–297.

Cline, T. L., Ludwig, G. H., and McDonald, F. B.: 1964, 'Detection of Interplanetary 3 to 12 MeV Electrons', *Phys. Rev. Letters* **13**, 783.

Fichtel, C. E.: 1964, 'Charge Composition of Energetic Solar Particles', in *AAS-NASA Symposium on the Physics of Solar Flares* (edited by W. N. Hess), NASA, Washington, pp. 263–272.

Krimigis, S. M.: 1965, 'Interplanetary Diffusion Model for the Time Behavior of Intensity in a Solar Cosmic Ray Event', *J. Geophys. Res.* **70**, 2943–2960.

Lin, R. P. and Anderson, K. A.: 1966a, 'Evidence for Connection of Geomagnetic Tail Lines to the Interplanetary Field', *J. Geophys. Res. Letters* **71**, 4213–4217.

Lin, R. P. and Anderson, K. A.: 1966b, 'Electrons >40 keV and Protons >500 keV of Solar Origin', *Solar Physics* **1**, 446–464.

Ludwig, G. H.: 1963, 'The Orbiting Geophysical Observatories', *Space Science Rev.* **2**, 175–218.

MASLEY, A. J.: 1966, Private communication.

McDONALD, F. B.: 1963, *Solar Proton Manual, NASA Technical Report R*-169, NASA, Washington.

McDONALD, F. B.: 1966, 'Solar Cosmic Ray Events near Minimum', in *AAS Symposium on solar astronomy*.

PARKER, E. N.: 1963, *Interplanetary Dynamical Processes*. Interscience Pub., New York.

WEBBER, W. R.: 1964. 'A Review of Solar Cosmic Ray Events', in *AAS-NASA Symposium on the Physics of Solar Flares* (edited by W. N. Hess), NASA, Washington, pp. 215–256.

WINCKLER, J. R.: 1967, Private communication.